DETECTING MICRO-STRUCTURE AND FLAWS IN COMPOSITES USING EDDY-CURRENT INSTRUMENTATION

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INTRODUCTION

Eddy-current inspection of advanced composite materials appears to overcome some of the difficulties typical of ultrasonic inspection. For example, carbon-carbon material can be inspected using eddy-currents without making the sample wet or using any acoustic coupling substances. Eddy-current inspection is very good for detecting fibers and fiber content because the fibers usually conduct electricity very well. Eddy-current measurements can therefore detect broken fibers in many cases where ultrasonic inspection fails to find the damage (broken fibers are not always good at scattering the ultrasonics). One of the common arguments against using eddy-currents to inspect composite materials is that they are unable to detect delaminations. This paper presents experimental evidence that suggests that delaminations *can* be detected with eddy-current inspection. Sabbagh [4] offer theoretical reasoning for the delamination behavior. This paper also presents some experimental data that indicates fiber structure, impact damage, and drilled holes in advanced composite material, including carbon-carbon and graphite-epoxy.

Composite materials are of interest to a number of industries for their strength and weight properties. The performance of these materials is obtained by combining strong fibers and a matrix "glue." The resulting material is difficult to inspect because its structure and electrical conductivity are nonhomogeneous. Our experiments apply eddy-current inspection to graphite-epoxy and carbon-carbon composites.

We describe our procedure and experimental results for gathering eddy-current measurements that indicate internal features of advanced composite materials. Our measurements of the EMF were made using inductive sensors, excited by various current sources, near samples of material. The EMF measurements, made in the range of 100kHz to 50MHz, indicate features such as fiber tows, impact damage flaws, drilled holes, and weave structure of the material. Laboratory data and model calculations are presented. Computer-controlled electronic instrumentation that uses phase-sensitive techniques measures the amplitude and phase of the induced sensor signal.

EXPERIMENTAL PROCEDURE

Multi-frequency phase and amplitude data were collected using a computer-controlled laboratory setup consisting of a custom phase-sensitive amplifier, a HPIB signal generator, a PC/AT-based 12 bit data acquisition system, an X-Y stepper motor positioning device, and numerous custom-made inductive pickup sensors. Sensors were mounted on the carriage of the X-Y positioner. The composite materials were fixed to the table of the X-Y positioner beneath the sensors. Measurements were made primarily using a "bi-static" arrangement in which the sensor passively measured the magnetic field in the presence of a separately driven exciting coil. Today's conventional approach to eddy-current measurements typically treats one coil as both an excitation and a sensor by driving a current through the coil and monitoring the impedance changes [1]. The bi-static arrangement allowed us to treat sensors and exciting coils separately [3]. The block diagram of Figure 1 shows the setup. A measurement was made by scanning the sensor over the material while making measurements with the computer-controlled instrumentation. The sensor was positioned at discrete points in X and Y; at each point a range of measurements was made by varying the excitation frequency and voltage. In most cases, we attached the sensor to the X-Y carriage and scanned over the sample. This method worked for samples that were flat. For samples with a curved surface, we mounted the sensor to a flexible "flap" that was held against the sample with a weight and was able to move up and down with the curvature of the sample.

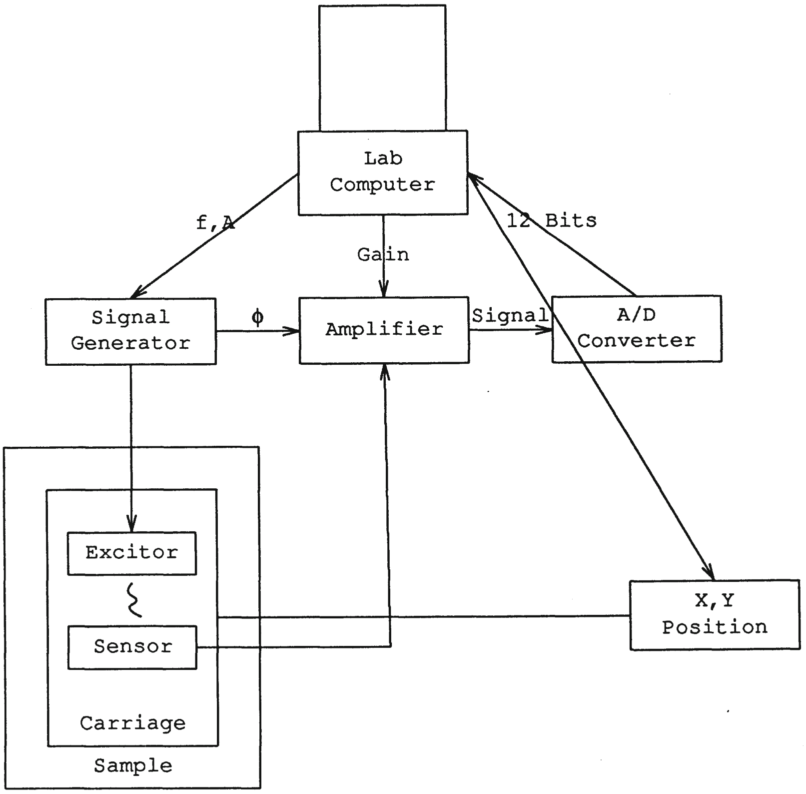


Figure 1. Block diagram of the laboratory setup. A phase-sensitive amplifier converts AC sensor signal into two DC voltages for the A/D converter. The signal generator and sensor position are under computer control.

Typical scans for defects in the material were with the sensor attached to the excitation. We also did a number of tests that we termed "anisotropy tests" that were performed by fixing the excitation to the sample and moving only the sensor. The typically circular exciting coil was either beneath or above the sample; we either measured the transmitted or reflected magnetic field, respectively.

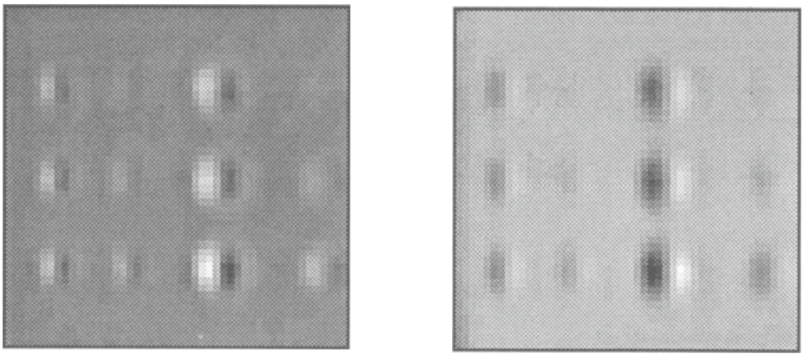
We attempted to detect delaminations using two different experiments. The first experiment was a comparison of transmitted magnetic field through different regions of a sample known to have delaminations. The sample that we used for the test had several artificial delaminations, formed by inserting a thin layer of Teflon between layers during the manufacturing of the sample. An excitation was placed beneath the sample, and sensors on the top side measured the transmitted magnetic field normal to the material surface. The sample was then moved to a new location (keeping the same spatial registration between the excitation and the sensor while transmitting through a new region of the sample) and the measurement was repeated. The process was repeated several times, measuring fields transmitted through several delamination regions and several non-delamination regions. These measurements were compared on a sums-of-squares basis; pairs of measurements were subtracted on the computer and the sum of squares of differences over the image was computed. This sum is a very simple measure of the difference between the two measurements. The assumption is that the number obtained can be compared to a threshold value to determine if one of the measurements comes from a delamination. Here we assume that the delamination is the only important factor contributing to a difference signal. The different regions were measured using a consistent laboratory setup; only the position of the sample varied.

The second setup for detecting delaminations was a multifrequency X-Y scan over the material with a bi-static sensor/excitation. We compared results with known locations of artificial delaminations.

EXPERIMENTAL RESULTS

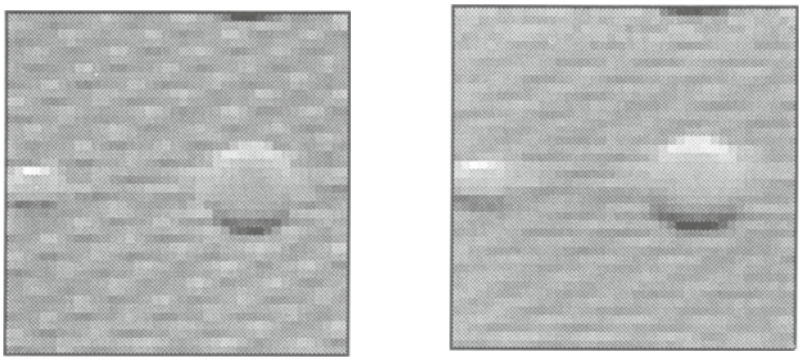
Data collected from a sample of satin weave graphite-epoxy material are presented in Figure 2. The images presented are grayscale plots made in *PostScript* (trademark of Adobe Systems Incorporated). The data presented in Figure 2 represents the EMF measured above the satin weave sample at a frequency of 2MHz, both in-phase with the exciting coil current and ninety degrees out of phase with the excitation current. The weaves that form the satin weave material can be seen in some of the eddy-current scans. Figure 3 gives a nice picture of the weaves, which were "over four, under one;" it is possible to determine the weave by measuring the distance between peaks in the image.

So that we had a good understanding of the material that we were measuring, we had two special samples made to our specifications. Both samples were made of alternating +/- 22.5 degree layers of graphite-epoxy construction. These two samples were each made of 18 alternating unidirectional layers; the two samples were identical in construction. We verified that we could model the material by predicting the magnetic field from a transmitted anisotropy test and comparing the model results to laboratory data. The results from this comparison are presented in Figure 4. The model prediction was based on treating the conductivity of the material as a bulk. In certain cases, agreement between model and experiment only occurred when we used a model that took into account the conductivity layer-by-layer [5]. An example is presented in Figure 5. We obtained the "fourfold" symmetry of the transmitted field only when modeled with a multi-layer model of the material.



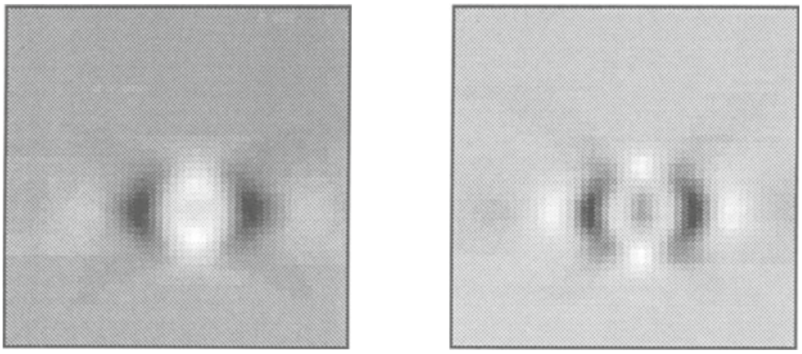
(A) (B)

Figure 2. Eddy-current EMF images collected over a sample of "satin weave" graphite-epoxy material. The sample had twelve flat-bottom holes of 0.5" and 0.25" diameter, ranging in depth from 0.02" to 0.12". (A) represents the in-phase portion of the signal (referred to the exciting coil current); (B) represents the quadrature portion of the signal.



(A) (B)

Figure 3. Eddy-current EMF images collected over a sample of "satin weave" graphite-epoxy material showing weave detail.



(A) (B)

Figure 4. Transmitted anisotropy measurements from a +/- 22.5 degree layup graphite-epoxy sample. (A) in-phase; (B) quadrature.

To test for damage, one of the two panels was kept undamaged while the other panel was damaged various ways. A region of the damaged sample covering an impact area (the impact was imparted with a blow from a ballpene hammer after cooling the sample with dry ice) is presented in Figure 6. The signal from the damage is quite visible in the corner of the scan region. Diagonal lines are present in the scans that appear in most scans of unidirectional layup material and are always in the fiber directions. We assume that these lines are from the fiber "tows" (bundles of fibers used to construct the material). We found it possible to also detect fibers in carbon-carbon samples, as indicated in Figure 7. The fibers show up in the image as streaks that curve near the top. Since the matrix of carbon-carbon conducts approximately as well as the fibers, the signals from the fibers is less than in graphite-epoxy.

Figure 8 shows the result of experiments done to detect delaminations. The plot represents the sum of squares of differences between pairs of images, some of which were delaminated regions and some of which were not delaminated. The X axis is the frequency in kHz. Each data point represents an average image difference; the differences were plotted of pairs of background-background regions (bottom) and delaminated-background regions (top). The increased difference between the background and delaminations implies that there is a detectable effect from the delaminations. Despite the success of this test for delaminations, we have so far been unable to *detect* the delaminations from a typical eddy-current scan.

CONCLUSIONS

Eddy-current inspection can be a very useful tool for evaluation of composite materials since information about the fiber structure can be obtained from the measurements. An eddy-current measurement can give indications of fiber breakage, electrical conductivity, fiber density, layer thickness, and perhaps delaminations. The layer-by-layer detail of the material *is* important in modeling the electromagnetic field in the vicinity of the material. For the eddy-current techniques to be effective at detecting defects, the damage must cause a change in the conductivity of the material.

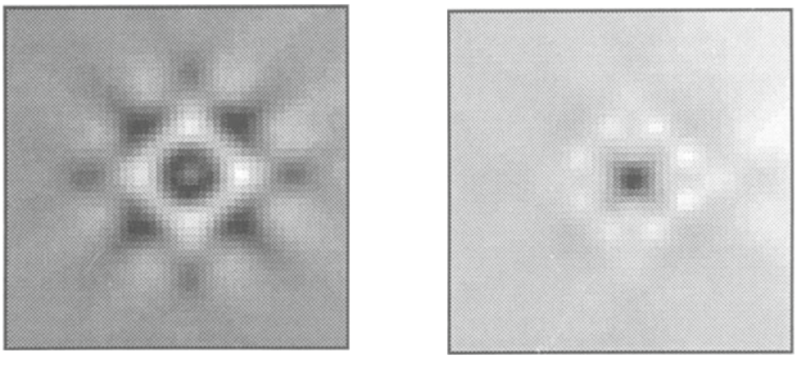
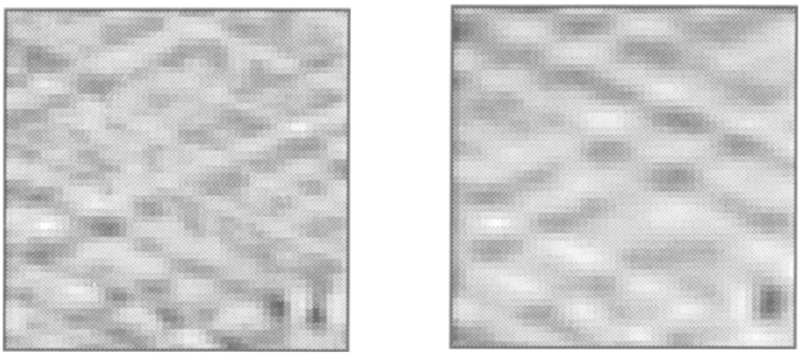
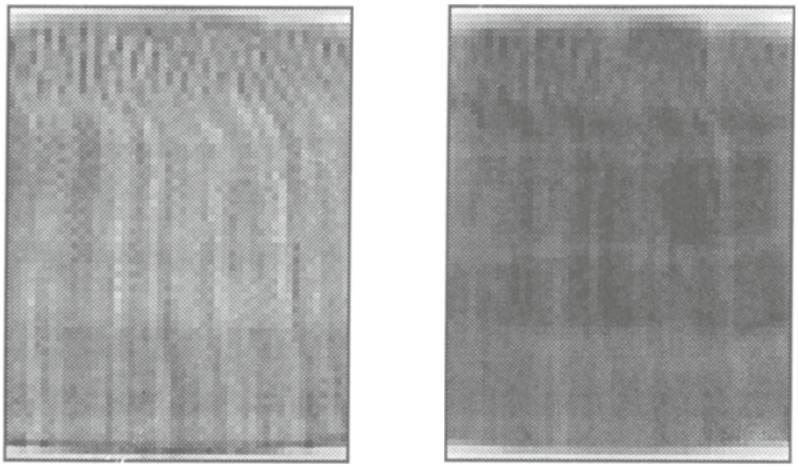

(A) (B)

Figure 5. Transmitted anisotropy measurements from two stacked samples of graphite-epoxy material. The "fourfold" symmetry of the field was modeled with a layer-by-layer computer model of the material.



(A) (B)

Figure 6. Eddy-current EMF images collected over a sample of +/- 22.5 degree layup graphite-epoxy material. The sample had impact damage in the lower right corner. The damage shows up in the grayscale plots. Lines in the images are in the two fiber directions and are thought to be from fiber "tows".



(A) (B)

Figure 7. Eddy-current EMF images collected over a carbon-carbon component. The component had fibers that were not straight and thus the strength of the piece was reduced.

Delaminations in the material probably only slightly change the Z-directed conductivity of a composite, thus making the delaminations difficult to detect. Z-directed eddy-currents in the composite material often have less magnitude than the in-plane currents, also making delaminations difficult to detect. Though difficult to detect, experimental evidence suggests that delaminations can be detected using eddy-current inspection. The partial success in finding delaminations with eddy-currents could probably be improved by using image classification and detection techniques.

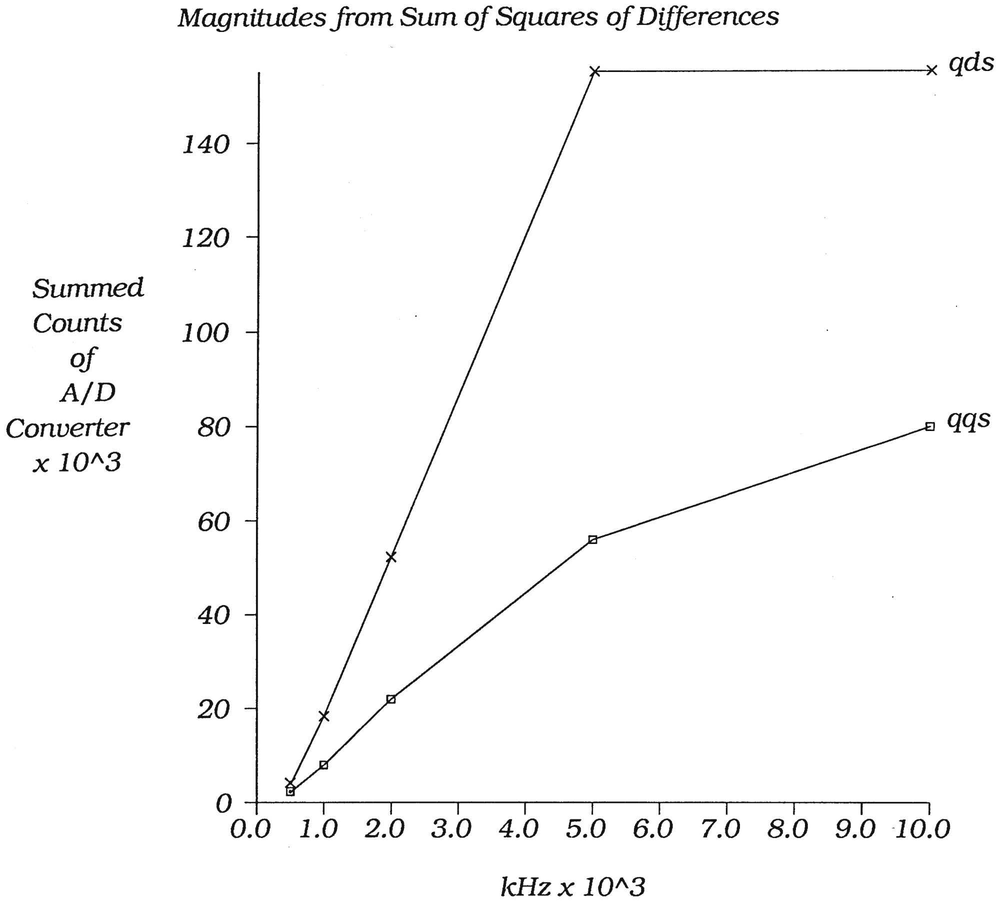


Figure 8. Sum of squares of differences between sets of measurements. The larger differences represent difference between the background signal and a delamination region. The smaller differences represent the approximate uncertainty; the smaller numbers are the sums of squares of differences between two background regions.

Signals resulting from fiber tows can usually be seen in eddy-current images. These tow signals can be used to determine fiber direction and perhaps information about layup order (if a range of frequencies is used). When the layup is not of unidirectional layers (e.g. satin weave), the images can reveal the fiber structure. These fiber signals can be either desirable or a difficulty when inspecting material for damage. When detecting a small region of damage to the material, it can be difficult to separate the "damage" signal from the "tow" signal.

Eddy-current technology is advancing to meet the needs of new material inspection. Since eddy-currents are primarily affected by fibers in the material, the technology proves useful as a companion to ultrasonic inspection. Eddy-current inspection can provide some information that can not conveniently be measured with other methods: electrical conductivity, fiber directions, and fiber content and breakage.

ACKNOWLEDGEMENT

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